Decay of hot, rotating, compound nuclei

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Abstract

The fusion process and the competition between fission and n, p and α–particle emission is studied. The calculations are performed for nuclei at excitation energies from 80 MeV up to about 300 MeV. The nuclear fission is described by a Langevin equation coupled to the Master equation for particle evaporation. A significant influence of the initial spin distribution on the prescission particles multiplicities is found.

1 Introduction

The present paper is a continuation of our previous work [1, 2]. We are studying systems with excitation energies of the order of (80–300) MeV. We assume that the particle emission is described by the Weißkopf theory [3], and that the nuclear fission is a transport process [4]. The emission of photons is neglected because at these excitation energies the particle evaporation is expected to be dominant.

Grangé and Weidenmüller [5] were the first point out the importance of the non–statistical aspects of the fission process. Our model and also the ones of Fröbrich, Abe and Carjan [6, 7, 8] are based on their work. In the last years one can observe the increasing amount of experimental studies of the evaporation of light particles from excited nuclei and of the concomitant decay by fission [9]. Results of our calculations are presented and compared with experimental work, especially that one of Ref. [10]. The present research is closly correlated with the measurements performed by the DEMON group in Strasbourg [11].

In our model we assume that the fission process is described by a Langevin equation which is dynamically coupled with a Master type equation for the light particles

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evaporation. We take into account the dependence of the evaporation probabilities on the deformation of nucleus, on its excitation and collective rotation. We assume that the transmission coefficient depends on deformation and on collective rotation of nucleus. The collective potential of the fissioning nucleus is evaluated within the model of a deformed, hot and rotating liquid drop [14]. The effective one–dimensional path to fission is chosen in a three–dimensional deformation space. The collective inertia is obtained in the irrotational flow model and the wall formula [12] is used to evaluate the strength of the friction forces. The Einstein relation between the friction and diffusion parameters is assumed to hold.

2   Results

We study the decay of the compound nuclei ^{160}Yb and ^{126}Ba at various excitation energies ranging from 80 MeV to 300 MeV. It is of special interest to investigate the influence of deformation and fast rotation on the emission of n, p and α–particles from excited states of these nuclei.

2.1   Decay of ^{160}Yb

We have selected this nucleus because a careful experimental investigation of its decays is available [10] and because it has a large ground state deformation. In Fig. 1, the deformation dependent emission width for n, p and α is shown for two different isotopes of both $_{64}$Gd and $_{70}$Yb. These 4 nuclei were chosen in order to illustrate how the deformation dependence of the emission widths for n,p, and α varies with the neutron and proton number of the emitting nucleus. All the emission rates grow as a function of increas-
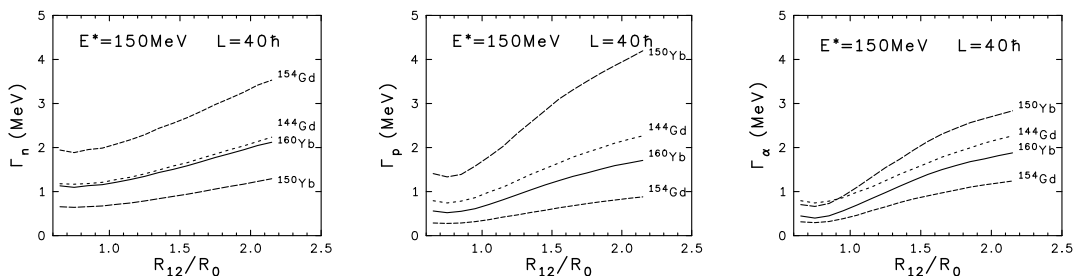

Figure 1:

ing deformation. This trend can be easily understood as for increasing deformation the transmission occurs through a larger surface. The effect has already been observed for all three types of particles [13]. We notice, however, that the emission width for α–particles increases more steeply than the one for n and p for lower excitation energies. This is due to the fact that, as the nucleus is elongated, the barrier height for charged particles is

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reduced in the section of the surface which is farther away from the nuclear center and increased in the section which is closer to the center. Consequently, the emission rate for charged particles increases faster than the one for neutrons.

The dependence of the number of decays of a given type on the time which elapses starting from the formation of the compound nucleus is unfortunately not measurable. Nevertheless, it is interesting to study this dependence theoretically in order to illustrate the time scale of this process. In Fig. 2 we show the number of fission events as a function of the time t on a logarithmic scale. This result was obtained with the light-
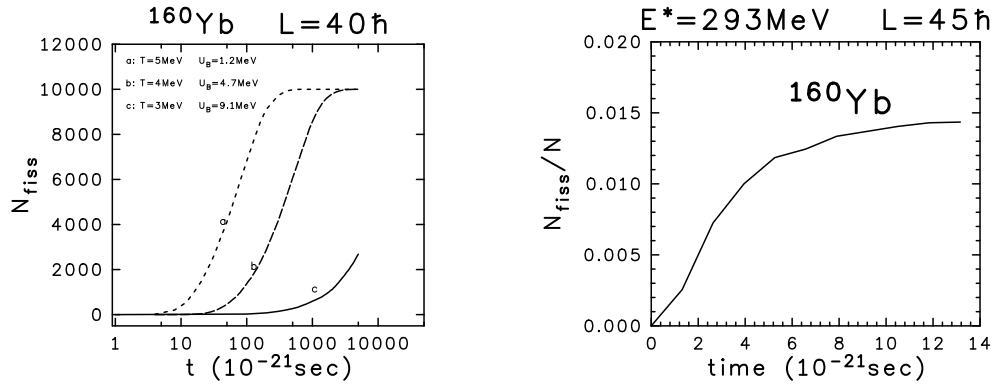

Figure 2:

particle evaporation channels turned off. The initial compound nucleus is $^{160}_{70}$Yb with an initial angular momentum $L = 40\,\hbar$. The three curves on the l.h.s. of Fig. 2 correspond to 3 different initial temperatures resulting in 3 different initial fission barrier heights U_B. It is seen that the transient time increases with decreasing excitation energy, as one expects. Please note that the transient time interval is seen to be totally different from the one in the Kramers regime. The Kramers limit is valid in the cases when the fission barrier is much higher than the temperature of the fissioning nucleus. On the r.h.s. of Fig. 2 the fraction N_{fiss}/N of nuclei undergoing fission is shown for the initial compound nucleus $^{160}_{70}$Yb as a function of time. Now, contrary to the results presented in the l.h.s. of Fig. 2, the emission of light particles is taken into account. This implies that the fission barrier rises as a function of time, since, at each particle emission act, the excitation energy and (on the average) the angular momentum of the emitting nucleus decreases. Consequently, the time scale of the fission process is stretched. The initial excitation energy of the nucleus is $E^\star = 293$ MeV ($T \approx 5$ MeV) and the initial angular momentum $L = 45\,\hbar$ is assumed.

The multiplicity of prefission neutrons, protons and α–particles is plotted in Fig. 3 as a function of the initial angular momentum L. The initial compound nucleus is $^{160}_{70}$Yb with the initial excitation energy E*=251 MeV (l.h.s.) and 293 MeV (r.h.s.). As to be seen in Fig. 3, the neutron multiplicity decreases significantly with growing L while that for protons and α–particles is much less affected. This is due to the fact that for large
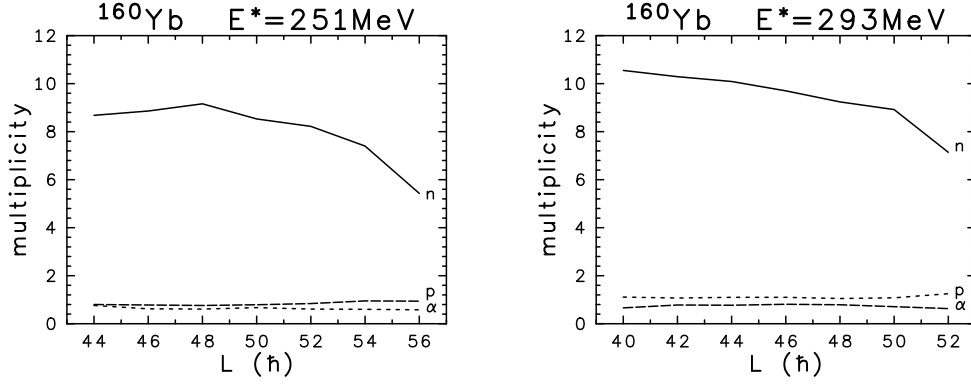
Figure 3:

angular momenta the fission barriers U_B become small and it takes a shorter time to reach the scission configuration. Consequently less neutrons are emitted on the average when the fission barrier is small. α–particles and protons are mostly emitted in the initial stage when the excitation energy of the nucleus is large, so that their multiplicities depend less strongly on the initial L.

This result indicates that a more precise knowledge of the initial spin distribution in compound nuclei is necessary for a meaningful comparison with experiment. For the case of ^{160}Yb the reduction of the fission barrier (U_B) by fast rotation has the consequence that only the largest L values contribute to the measurable values of the multiplicities as one can see in Fig. 4. The theoretical estimates of the prefission particle multiplicities,
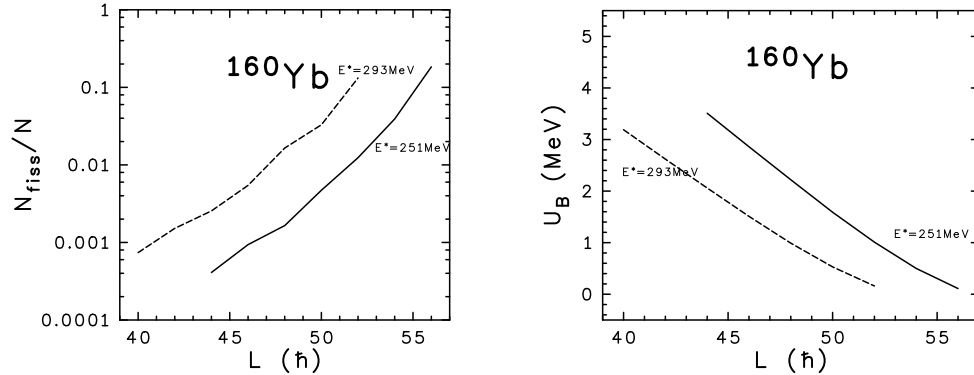

Figure 4:

averaged over all angular momenta of compound nucleus, are compared in Table 1 with the experimental data taken from Ref. [10].

All parameters of the model are given in Ref. [14]. We only have to choose a

	E^*=251 MeV		E^*=293 MeV	
ν	model	exp.	model	exp.
n	5.98	6.10$\pm$ 1.5	7.80	8.50$\pm$ 1.6
p	0.94	0.51$\pm$ 0.07	1.19	0.70$\pm$ 0.08
α	0.58	0.48$\pm$ 0.07	0.66	0.75$\pm$ 0.08

preformation factor $f_\alpha = 0.2$ for reproducing the experimental number of α–particles. This goes into the right direction since our calculations show that α–particle emission is strongly enhanced by rotation and deformation effects. One of the most important further improvements of the theory will be to evaluate this preformation factor within the temperature–dependent Thomas–Fermi approximation which underlies our theory [15]. At low temperature, the Thomas-Fermi approximation is expected to yield too low values of the preformation factor. Additional effects like the pairing correlations will then increase the value of the preformation factor at low excitation energies (T $\leq$ 1 MeV).

In the l.h.s. of Fig. 5, we present the energy spectra of neutrons (n), protons (p) and α–particles emitted by fissioning nuclei (solid lines) and by the fission residua (dashed lines).
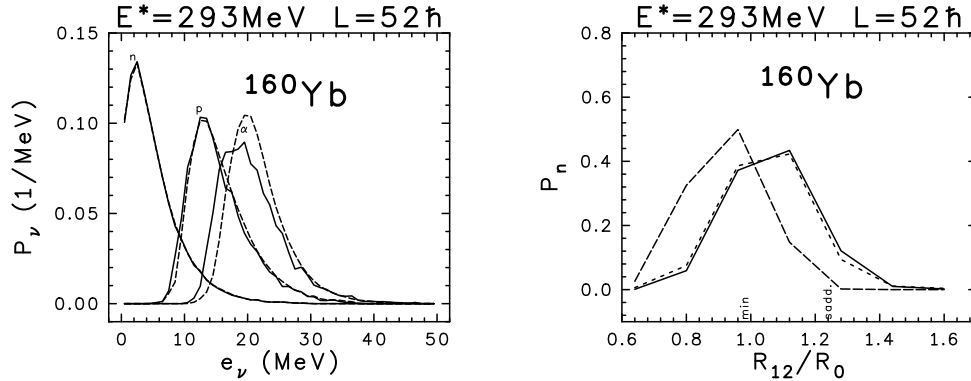

Figure 5:

The spectral distribution for α–particles emitted in coincidence with fission is shifted by about 2 MeV towards smaller energies as compared to the distribution obtained when measured in anti-coincidence with fission, while for neutrons the both distributions are very close to each other. This is due to the fact that charged particles are preferentially emitted from the pole tips around the long half axis. The larger deformation then implies a smaller gain of kinetic energy from the repulsive Coulomb field.

In the r.h.s. of Fig. 5, the normalized yield for neutron emission is shown as a function of the nuclear deformation in the fission and evaporation channels. One can notice that for nuclei which undergo fission, the emission of neutrons takes place, on

the average, at a larger deformation than for the nuclei which end up as evaporation residues. This is due to the fact that the distribution of the fissioning nuclei moves towards the saddle point, i.e. into a region of increasing deformation. This effect should give rise to an experimentally observed anisotropy in the angular distribution of prefission particles different from the one observed in the angular distribution of particles emitted by the evaporation residua: We expect that less neutrons will be emitted in the reaction plane than in the direction perpendicular to this plane. The anisotropy in the angular distribution of the charged particles will be probably smaller than that in the neutron case. This is due to the fact that the enhanced emission of α and p from the tips of the nucleus reduces partly the effect of its deformation. The distribution for the case when the emission of protons and $\alpha-$ particles is inhibited is shown on the r.h.s. of Fig. 5 by the short–dashed line. It is seen that this distribution is very close to the one obtained when the emission of all three kinds of particles is allowed.

2.2 Decay of ^{126}Ba

In the last months a new experiment on fusion and decay of ^{126}Ba was performed at the VIVITRON accelerator of the CRN in Strasbourg. The DEMON facility was used to detect the outgoing neutrons [11]. Two types of reactions were studied:

- ^{28}Si + ^{98}Mo at E_{lab}= 142.*, 165.8, 187.2 and 204 MeV,

- ^{19}F + ^{107}Ag at E_{lab}= 128.0 and 147.8 MeV

In this way the compound nucleus ^{126}Ba was produced at four different excitation energies E^*= 84.1, 101.5, 118.5 and 131.7 MeV. The spin distribution differs in each case since it depends on the energy and on the way in which the compound nucleus was produced.

As the results of these experiments are still analyzed, and neither fusion cross sections nor multiplicities of outgoing particles are avaible, we have estimated the fusion cross section using our model described in [16, 17]. The Langevin transport equation was used to describe the fusion process. The effect of deformation of the colliding ions was taken into account [17]. The results of this numerical simulation are presented in Fig. 6, where the differential cross section is plotted in form of bins as a function of L for the six different ways in which ^{126}Ba was fused. Each simulation was performed on basis of 30.000 trajectories. The total fusion cross section σ_{fus} as well as the average angular momentum and its variance are written in the upper left corner of the plots. We have also fitted these fusion cross sections by the function (solid line)

$$\frac{d\sigma}{dL} = \frac{a \cdot L}{1 + e^{\frac{L^2 - b^2}{c^2}}} \ .$$

The parameters a, b, c characteristic for each distribution are written in the upper right corners of the plots. We can see in Fig. 6 that the distribution of the angular momentum L is different in each case. We predict that the maximal angular momentum of the fused system varies from about $60\hbar$ up to $100\hbar$ depending on the way in which ^{126}Ba is produced.
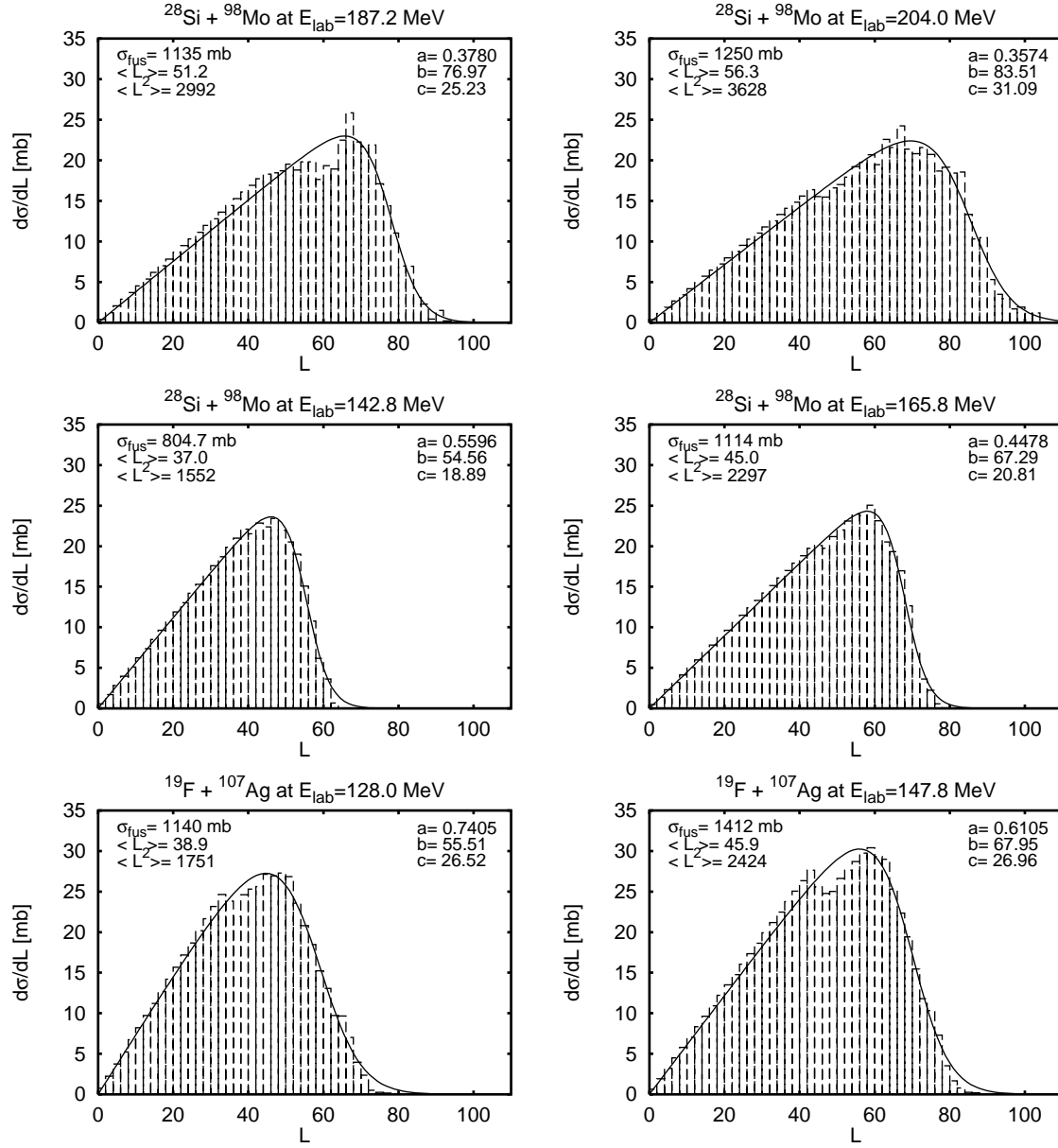
^{28}Si + ^{98}Mo at E$_{lab}$=187.2 MeV

σ_{fus}= 1135 mb
< L >= 51.2
< L^2 >= 2992
a= 0.3780
b= 76.97
c= 25.23

^{28}Si + ^{98}Mo at E$_{lab}$=204.0 MeV

σ_{fus}= 1250 mb
< L >= 56.3
< L^2 >= 3628
a= 0.3574
b= 83.51
c= 31.09

^{28}Si + ^{98}Mo at E$_{lab}$=142.8 MeV

σ_{fus}= 804.7 mb
< L >= 37.0
< L^2 >= 1552
a= 0.5596
b= 54.56
c= 18.89

^{28}Si + ^{98}Mo at E$_{lab}$=165.8 MeV

σ_{fus}= 1114 mb
< L >= 45.0
< L^2 >= 2297
a= 0.4478
b= 67.29
c= 20.81

^{19}F + ^{107}Ag at E$_{lab}$=128.0 MeV

σ_{fus}= 1140 mb
< L >= 38.9
< L^2 >= 1751
a= 0.7405
b= 55.51
c= 26.52

^{19}F + ^{107}Ag at E$_{lab}$=147.8 MeV

σ_{fus}= 1412 mb
< L >= 45.9
< L^2 >= 2424
a= 0.6105
b= 67.95
c= 26.96

Figure 6:

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The initial temperatures of the compound nucleus ^{126}Ba are rather low as the total excitation energy of the system is not very high and a large fraction of the excitation energy is stored in the form of rotational and deformation energy. Fig. 7 illustrates how the temperature of ^{126}Ba changes as function of the the angular momentum L for given excitation energy. For each L value the corresponding equilibrium deformation was chosen. It is seen that for the angular momenta $L \geq 80$, which contribute mostly to fission
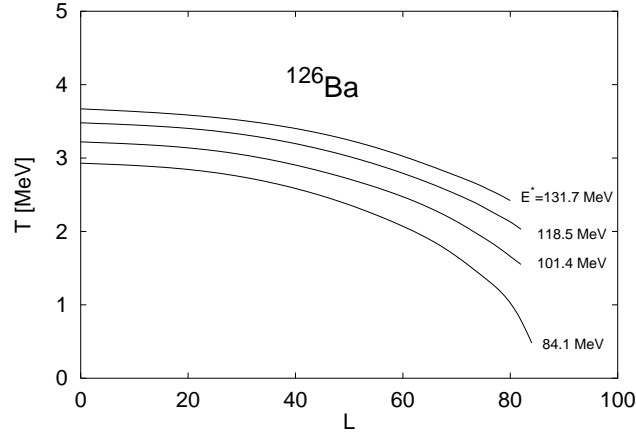

Figure 7:

of ^{126}Ba, and the lowest excitation energy E^*=84.1MeV the initial temperature reaches the value $T \approx 0.5$ MeV. At such a low temperature our model (transport equation for fission without superfluidity coupled with the Master equation for particle evaporation) is poorly justified. So one should cosider the estimates of the prefission particles we obtained for this energy as only a rough estimate.

Theoretical estimates of the multiplicities of neutron, proton and α–particles are given in the table:

Reaction	E_{lab}	E^*	M_n	M_p	M_α	S_n	S_p	S_α
	MeV	MeV	-	-	-	-	-	-
	204.0	131.7	2.29	0.03	0.79	2.30	0.11	4.11
^{28}Si + ^{98}Mo	187.2	118.5	1.71	0.00	0.09	2.19	0.09	3.71
	165.8	101.4	1.83	0.00	0.04	2.13	0.05	3.20
	142.8	84.1	0.27	0.04	0.88	2.23	0.02	2.56
^{19}F + ^{107}Ag	147.8	118.5	1.99	0.00	0.16	2.13	0.09	3.84
	128.0	101.5	1.80	0.01	0.06	2.11	0.05	3.30

The thermal excitation energies of ^{126}Ba are rather low, so we have assumed here the preformation factor for α–particles f_α=1 as for cold nuclei. Just for comparison we have presented also the multiplicities of these particles (S_i, $i = n, p, \alpha$) connected with the

evaporation residua. One can see from the table that a rather large number (≈ 4) of α–particles is emitted by the residua. It is due to the fact that the nucleus ^{126}Ba has a rather small Coulomb barrier for of α–particles. Furthermore, the large average orbital momentum of the mother nucleus favors the emission of α–particle. Due to these two effects even the emission of α–particles with very low kinetic energy becomes possible. As a consequence the α emission competes significantly with neutron emission and becomes even larger for the evaporation residua.

If the particles are emitted in coincidence with fission they are emitted at very large deformation ($R_{12} \approx 2$), wheras if they are emitted in coincidence with evaporation residua the emission occurs at smaller deformation ($R_{12} \approx 1.2$). This effect could be observed in the angular distribution of emitted neutrons: More particles should be emitted in the direction perpendicular to the reaction plane as in the reaction plane. This effect will not be so visible for α–particles because the reduction of the Coulomb barrier is largest at the tips of the highly deformed nucleus and at the same time the collective centrifugal force acting on the α–particle is the largest in this peripheral region what favours emission in the reaction plane.

Summary

Our results demonstrate the influence of the nuclear deformation and of the collective rotation on the evaporation of light particles from excited nuclei. The dependence on the deformation plays an important role also for the competition between fission and particle emission and might modify the limits which were determined for the nuclear friction force [1] from the experimental data on evaporation and fission.

Due to the strong dependence of the fission probability on the initial angular momentum, it is very important to obtain a precise information on the angular momentum distribution of the initial ensemble of compound nuclei. The outcome of the competition between light particle emission and fission depends strongly on the initial angular momenta. The reason is that the rotational angular momentum of the nucleus has a very noticeable influence on the height of the fission barrier which decreases as a function of increasing angular momentum. Thus, at high angular momentum, nuclear fission can compete more effectively with evaporation.

We hope that the angular distribution of emitted particles, especially neutrons, depends on the deformation of the source nuclei sufficiently sensitively so as to determine the deformation from such measurements. The experimental data on the angular distribution of emitted neutrons, protons, and α–particles from aligned rotating deformed nuclei would be of great interest for these studies.

Acknowledgment

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